TIME-BASED SERVOPOSITIONING SYSTEMS

5 ## FIELD OF THE INVENTION

This invention concerns systems and methods for time-based servopositioning in the context of linear data recording media such as magnetic tape.

BACKGROUND OF THE INVENTION

Modern data storage systems use servopositioning (or "servo") systems to guide

10 their recording and playback components with respect to a recording medium, and thus enable high track density, which increases data storage capacity. Errors in the ability to follow the servopositioning signals on the medium can cause unacceptable reductions in storage capacity, recording/playback rates, and other parameters that are important to consumers (and thus to system manufacturers).

15 One type of servo patterns or formats for linear magnetic tape recording systems employs so-called time-based servo techniques, examples of which are disclosed in US Patents 5,689,384; 5,930,065; and 6,021,013 (all of which are incorporated by reference in their entireties). Commercial magnetic tape drives such as the IBM model 3570 and drives known under the names "Ultrium" and "Accelis," as described by the Linear Tape

20 Open consortium, use time-based servopositioning systems.

The advantages of time-based servo systems include very wide dynamic range; inherent track identification; low DC centerline error; and the ability to qualify position error signal (PES) validity by the amplitude of the servo signal. Disadvantages include

extreme sensitivity to tape speed during writing; sensitivity to high frequency speed error during reading; and poor scalability to very small track pitches.

SUMMARY OF THE INVENTION

In general terms, the invention may be embodied in time-based servopositioning systems, methods, and formats, or in data recording media used in association with the same, and therefore this disclosure should be understood in that regard even if only an example of a particular embodiment is described in detail. Similarly, this disclosure should be understood to apply to either analog or digital signals, in accordance with principles known in the art. Thus, the terms "signal," "data," and the like may be used interchangeably, and should be understood to apply to either analog or digital representations of information.

In the most basic embodiment of the invention, a servopositioning system for a data recording system is used in combination with a linear data recording medium, preferably magnetic recording tape. Written or recorded on the medium are a timing reference (for example, a high frequency AC "pilot tone") and a conventional time-based servo signal. Appropriate circuitry is separately responsive to the two signals so they can be separated from each other. The circuitry produces position error signals by sampling the time-based servo signal at a sampling rate, and also increases the bandwidth of the timing reference signal above that sampling rate. In the preferred embodiment, the two types of signals are written onto the same location of the recording medium, but the high frequency pilot tone signal is written such that its frequency lies in a playback null of the time-based servopositioning system. Any technique for accomplishing this is suitable, but in the most preferred embodiment the two signals are recorded at different azimuth angles with respect to each other (*i.e.*, relative to the playback head of the system).

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BRIEF DESCRIPTION OF THE DRAWINGS

The accompanying drawings show a particular embodiment of the invention as an example, and are not intended to limit the scope of the invention.

Figure 1 is a schematic diagram of one embodiment of the invention.

5   Figures 2a, 2b, and 3 are schematic views of geometric aspects of the embodiment of Figure 1. Figure 2b is an enlarged view of the portion of Figure 2a indicated by the circle designated 2b.

Figure 4 is a schematic diagram of another aspect of the embodiment of Figure 1.

Figures 5 and 6 are schematic diagrams of a preferred embodiment of the 10   invention.

DETAILED DESCRIPTION

In general terms, the invention can be embodied in an entire system of data recording and playback, including the combination of a drive and a linear recording medium; or as only the recording medium portion of such a system; or as methods for 15   recording or playing back data in combination with the data recording medium. Thus, while the following description may occasionally focus on only one aspect of an entire system (*e.g.*, the recording medium alone) to disclose the preferred embodiment of the invention, this is by way of example only, and not a limitation on the scope of the invention. It should be understood that the full scope of the invention includes other 20   aspects of the system depending on the circumstances, such as combinations of the medium and drive, and methods of using such combinations or relevant portions of them.

The time-based servo system described in US Patents 5,689,384 and 6,021,013 is somewhat immune to speed error (or time-based error) in playback by the use of a reference pulse to compare against the PES (Position Error Signal) pulse. The system is

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only somewhat immune, because as the frequency of the speed error increases up to the sample rate of the PES system itself, the natural immunity generated by the reference normalization procedure decreases.

Data recording systems using tape media can have considerable time-based error (also known as instantaneous speed variation, or ISV) at frequencies approaching commercially standard PES sample rates. The invention improves the time normalization performance (and thereby the immunity to ISV) of linear data recording systems by effectively increasing the reference time-based bandwidth until it is greater than the PES sample rate.

Figure 1 is a schematic view of one recording system embodiment suitable for this approach, using (for purposes of illustration only) magnetic recording tape as the preferred type of linear recording medium.

Recording system 20 comprises supply reel 21, tape 22, pilot tone recording head 23, time-based servo write head 24, verify head 25, and take-up reel 26. An AC bias signal 27 is the input to pilot tone recording head 23. A current pulse signal 29 is the input to time-based servo write head 24. Verify head 25 produces verify signal 30 that typically passes through a conventional preamplifier (not shown) to become input signal 41 of Figure 4 (described below).

Figures 2a and 2b schematically show a full-width servo band of height h superimposed on a "sea" of high-density pilot tone 2 produced by pilot tone recording head 23, which is subsequently used for playback speed tracking. The time-based servo pulses 6 produced by time-based servo write head 24 overwrite this tone. By way of example only, the servo pattern has five pulses 6 per sample 7. The high-density tone is largely unaffected by the servo pulses because the servo pulses are written using a return-to-zero technique meaning the write current is mostly turned off. In general, the high

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frequency signal **2** is recorded at a wavelength such that its frequency lies in a playback null of the time-based servopositioning system.

In the preferred embodiment, the two signals are recorded at different azimuth angles with respect to each other. Referring additionally to Figure 3, for a given read track width T_w and a given slant angle θ, there is a natural spatial frequency null at a wavelength λ_{HF} proportional to the read track width and the tangent of the slant angle θ, or $\lambda_{HF} = T_w * \tan(\theta)$. Thus, placing the pilot tone in the azimuth null of the time-based servo enables both signals to be available after suitable filtering. For example, given a read track width of 5 micrometers and an angle θ of ±8 degrees, λ_{HF} occurs at the reasonable density of 72,300 flux changes per inch (fci). This density is well within the capability of a tape and a head designed for >150kbpi data recording. At two meters/second media speed, this density corresponds to a frequency of 2.8MHz, easily enabling a phase locked loop tracking bandwidth above 50kHz, or approximately 10 times the typical ISV resonant frequency of the medium. These are examples only and not limitations on the scope of the invention.

A preferred system to fully utilize this signal structure is shown schematically in Figure 4 as circuitry **40**. Circuitry **40** receives an input signal **41** produced by the conventional read head preamp (not shown) as described above. This signal is input to both a band reject ("notch") filter **42** and a band pass filter **44**. Notch filter **42** eliminates the high density pilot tone component but has little effect on the time pulse, because the filter notch is at the same frequency as the natural azimuth loss notch. The filtered time pulse is thereafter processed normally, as described in US Patent 6,021,013, with one crucial difference; the measurement time base normally derived from an external clock is derived from the high-density signal.

Specifically, the portion of the signal that passes through band pass filter **44** is the input to a phase locked loop (PLL) **46** that produces a measurement time base signal **50**

for the time-based demodulator circuit **43**. The band pass is only wide enough to pass the signal and its anticipated FM sidebands, *e.g.* for the case above, 2.8MHz ± 100kHz. This narrow 200kHz bandwidth is more then eleven decibels quieter than the regular data channel, and therefore this reference tone signal has good signal -to-noise ratio, even when recorded at a low level. (The smaller read track width of the servo read head circuitry makes this narrow band high frequency signal perhaps only 8db better than the read channel at the same density.) The PLL locks onto this frequency and generates a frequency tracking reference clock for the time-based servo detector circuit. This clock could be any rational multiple of the recorded tone. For example, for the rational multiple of 107 to three, the reference clock signal will be 2.8 MHz x 107/3 = 99.8 MHz.

The high density signal actually serves at all times as a reference, and therefore has some advantages over the traditional "B interval" reference as described in US Patent 6,031,013, particularly at column 7, line 30 to column 8, line 2. First, the need for the "B interval" is eliminated altogether and replaced by the need to know when the "A interval" (or measurement period), as described in the same patent, begins. This enables a higher PES sample rate, because eliminating the reference measurement reduces constraints on the design of the format. Second, since the time-based reference is known at the same time that the PES measurement is known, and because a sampling delay appears to the servo system as if it were a phase lag, there is little PES sampling phase delay, by a factor of as much as one-half the sample time. This enables higher servo performance.

In the preferred embodiment of this scheme, and as taught in US Patent 6,021,013, multiple PES bursts are recorded together, such as in groups of four or five. The spacing between these pulses should be such that the pulses fall on unique phases of the high frequency tone. For example, if the first pulse in a group of four pulses falls on the zero degree phase of the high frequency signal, the second pulse should fall on the [N cycles plus] ninety degree phase of the next pulse. Similarly, the third pulse should fall on the [N cycles plus] 180 degree phase, and the fourth pulse at the [N cycles plus] 270

degree phase. Since the PES is calculated by taking the average of these four values, any possible bias caused by the high frequency tone may be averaged out according to known principles.

In another preferred embodiment of the invention, the pilot tone is modulated with a (preferably double) side band AM component without affecting the timing functionality, provided the modulation does not approach 100% negative, which would negate the pilot tone signal entirely. For example, as illustrated in Figure 5, pilot tone **27** is formed by combining an AC bias signal **28** (for example, a sine wave signal in the range of eighty to three hundred kfci) and modulation carrier **34** (for example, a sine wave signal in the range of approximately twenty to one hundred kfci). The modulation content may comprise linear position (or "LPOS") data, or auxiliary data (*e.g.*, manufacturing data) as indicated at **31**, and general purpose data such as synchronization signals and error correction/detection data as indicated at **32**. Other content may include encoding data as indicated at **33**, including "biphase" or Manchester encoding, NRZ, NRZI, PR4 and other known encoding techniques; however, quadrature amplitude ("I & Q") modulation schemes may not be desirable because the primary timing task of the carrier signal is adversely affected. Manchester encoding provides the advantage of simplified decoding due to the simpler embedded clock structure.

The resolution of the linear position data may be as coarse as 10cm to as fine as 1cm, although greater resolution requires greater bandwidth which is undesirable because it reduces the robustness of the signal. Assuming digital modulation bandwidth (double sided) of the pilot tone carrier of approximately 10 KHz and a tape speed of 2 m/s, Manchester encoding would encode 2.5 kbps or 1.25 bits/mm; thus, 125 bits would be encoded in a span of 10 cm, which is sufficient for an accurate LPOS signal. Other more sophisticated encoding schemes could produce as much as 50 bits/cm in the same bandwidth.

Figure 6 is a schematic diagram of the receiver for this embodiment. The AM signal first passes through band pass filter **44** and is an input to the phase locked loop **46**, which tracks its frequency and phase. The primary use of this input is to time the time-based servo pulses, as in the embodiment described above, and also to synchronously

5   demodulate the AM signal by use of an analog multiplier **47**. The output of analog multiplier **47** passes sequentially through a low pass filter **49**; a detector **51**; a channel code demodulator **52**; appropriate encoding **53** for data words, sync signals, and error correction codes, as applicable; and suitable LPOS counters and auxiliary text memory **54**. The result is an output signal **55** that is transferred to the drive controller of the system

10   (not shown).